**PHYSICAL CHARACTERISTICS OF CHONDRULES AND RIMS, AND AERODYNAMIC SORTING IN THE SOLAR NEBULA.**

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Chondrules are the dominant constituents of the very primitive “chondritic” meteorites, and show clear evidence for aerodynamic sorting. The least metamorphosed chondrites have had the fewest modifications since their formation and therefore retain more of their primary features than any other meteorites. We have examined separated chondrules from two CV3 chondrites (Allende and ALH 84028) and one L4 ordinary chondrite (ALH 85033). The radius*density distribution from all of the studied meteorites fits closely to the theoretical prediction (Figure 1). Rim volumes were calculated for a suite of chondrules disaggregated from Allende, and are approximately equal to the volume of the underlying chondrule.

It has been proposed that nebula wide turbulence concentrates chondrules and similar sized fragments by large factors into many small, dense, transient zones throughout the vertical extent of the nebula [1]. The validity of this process can be assessed by direct measurements on separated chondrules from meteorites.

This concentration process is highly size-selective and related to the aerodynamic stopping time of the particles. The stopping time, $t_s = r_p\rho_s/c\rho_g$, is actually determined by the product of the particle radius $r_p$ and density $\rho_s$; $\rho_g$ is the gas density, and $c$ is the speed of sound.

Turbulence selects particles with a specific stopping time for significant (orders of magnitude) concentration in a gas-dominated nebula. The actual mean sizes observed for chondrules (0.1 - 1 mm) follow directly from turbulent intensities (Reynolds numbers) which have been inferred recently by several different groups, for different reasons and under different assumptions [1]. A natural aspect of this process is the accumulation of rims of fine dust on such fragments; the rim thickness will be functionally dependent on the core radius through the relative velocity.

**Experimental procedure**. The goal of the project is to obtain size, density, textural, and compositional information on chondrules from a variety of meteorites. Simple measurement of chondrules in thin section does not provide accurate diameters. Any random cut through the chondrule, as would result from the thin sectioning process, results in a measured core diameter that is smaller than the actual diameter of the chondrule and a rim thickness that is larger than the actual rim thickness. This variance can be accounted for when dealing with large number of chondrules [2, 3], but is inappropriate when correlating features of chondrules with size. Neither is the density of chondrules available in thin section. Chondrules from Allende and ALH 84028 were obtained by freeze/thaw disaggregation, after [4]. Chondrules were picked from the available fines of ALH 85033 in the Antarctic collection at Johnson Space Center.

Measurements of chondrule sizes along two axes were done from photomicrographs. The volume was calculated using the average of the measurements. Each chondrule was weighed using a high precision Mettler balance, and the density calculated.

Polished sections of the objects were used to eliminate any objects that were not chondrules, determine the texture of chondrules, whether or not a rim was present, and perform major element chemical analysis of the major minerals in a select subgroup of the chondrules.

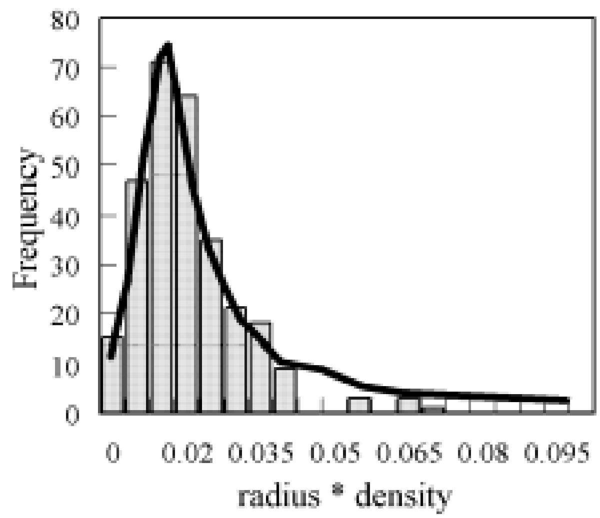


**Figure 1. Comparison of theoretical prediction of particle sizes that clump [5] with the measured product of the radius and density (the basis of the stopping time, $t_s$) of chondrules from the Allende meteorite.**

**Size sorting of chondrules**. Our studies [1] have shown that turbulent concentration of particles occurs which is strongly size-selective. This work must be done numerically due to the complicating (and irrelevant) effects of terrestrial gravity; the fluid Reynolds number accessible to numerical calculations is far lower than in the actual nebula. We have recently shown that certain key aspects of the process are *invariant to Reynolds number* [5]. Amongst these is the *shape* of the concentration factor within dense particle concentration zones as a function of particle stopping time. Figure 1 compares these recent theoretical results for the concentration factor (relative frequency) for particles with 16 different stopping times (heavy solid line) with our disaggregated chondrule size distribution data for Allende. We find the agreement most encouraging.

The mean diameter of disaggregated chondrules from the CV3 chondrites Allende (0.85 mm) and ALH 84028 (0.97 mm) are larger than chondrules separated from the L4 chondrites ALH 85033 (0.72 mm) and Bjurböle (0.688 mm, [2]). These values are consistent with previous work indicating that chondrules in CV chondrites are larger than those in ordinary chondrites [6, 7].

**Chondrule rimming**. We have calculated the actual rim thickness on a suite of chondrules for the first time, using the measured diameter of the chondrule and the measured thickness of the rim and core in the polished section. Previous work [8, 9, 10] measured apparent rim thickness as observed in thin section, which varies from the true rim thickness due to the random cut of a thin section of the meteorite through the chondrule (Figure 2).

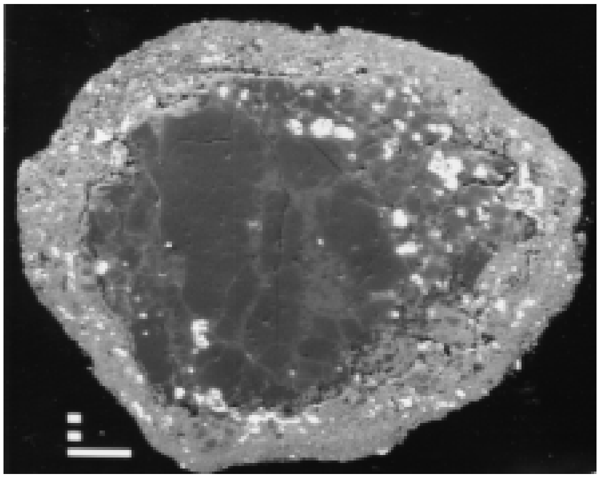

**Figure 2. Rimmed chondrule from the Allende meteorite. This porphyritic olivine chondrule has a very well developed accretionary rim. The scale bar is 100 µm in length.**

Chondrules selected for the calculation were subject to the criteria that the rim was accretionary (vs. rims resulting from chemical alteration) and surrounded at least 75% of the chondrule in the polished section. Results from chondrules with accretionary rims from the Allende chondrite are shown in Figure 3. The volume of the rim is approximately equal to the volume of the core for all samples studied. These results are consistent with the total volume percent of accretionary dust mantles determined by point counting thin sections of 14 CM chondrites [8].

One simplified model of dust sweep-up would predict that the growth rate of the mass (volume) of an accretionary dust rim would be proportional to the exposure time and sweep-up rate. The velocity of the core relative to the gas (plus embedded fine dust) is a function of the radius through the stopping time ($t_s = r_p \rho_s / c \rho_g$). Thus, if relative velocities are determined by turbulent fluctuations, the core volume might be expected to be proportional to $r_p^3$, as is indicated by our data (Figure 3).

Another model would assume that each chondrule must accrete its own mass in material before being "stopped." The accretion of material onto the core slows the chondrule down, and eventually stops its movement through the gas and dust, ending accumulation of rim material.

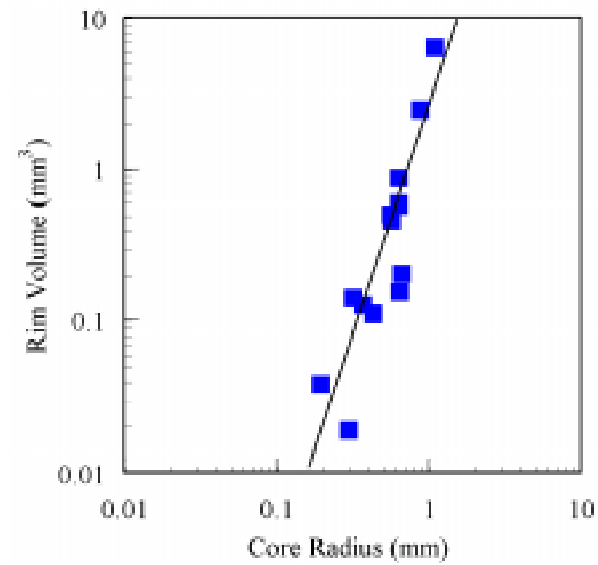


**Figure 3. Rim volume vs. core radius ($r_p$) for a suite of chondrules from the Allende meteorite. The rim volume is approximately equal to the core volume.**

**Summary**. The following conclusions can be drawn from our initial results:

A. The size-frequency distribution of chondrules has a similar shape across several meteorite classes, although the mean size differs.

B. These size-frequency distributions are in great agreement with theoretical predictions of turbulent concentration in the early nebula [1, 5].

C. The volume of the rimming material has been measured for the first time, and shows a strong correlation with the volume of the underlying core.

These techniques and results open up a new window on conditions in the protoplanetary nebula.

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